Rotating magnetic quadrupole RMF current drive for FRCs

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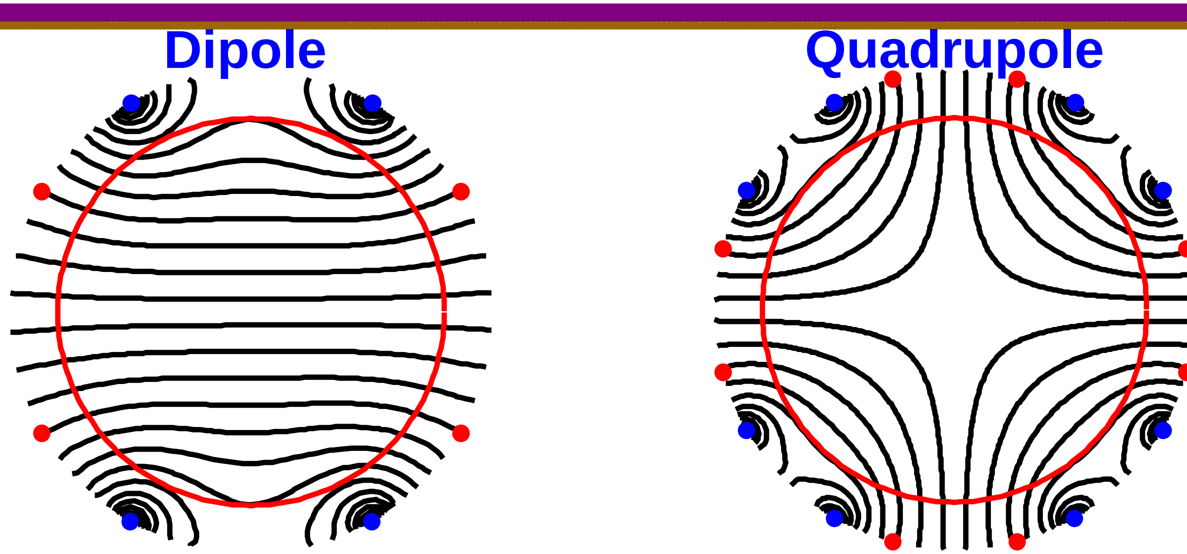
Outline

- Introduction:
  - What is Quadrupole RMF current drive?
- Why attempt quadrupole RMF current drive?
- Numerical Predictions
- Experimental observations
  - Comparable drive capability
  - More prone to n=2 instabilities
  - Large internal oscillations for some parameters
- Summary

Quadrupole vs. dipole

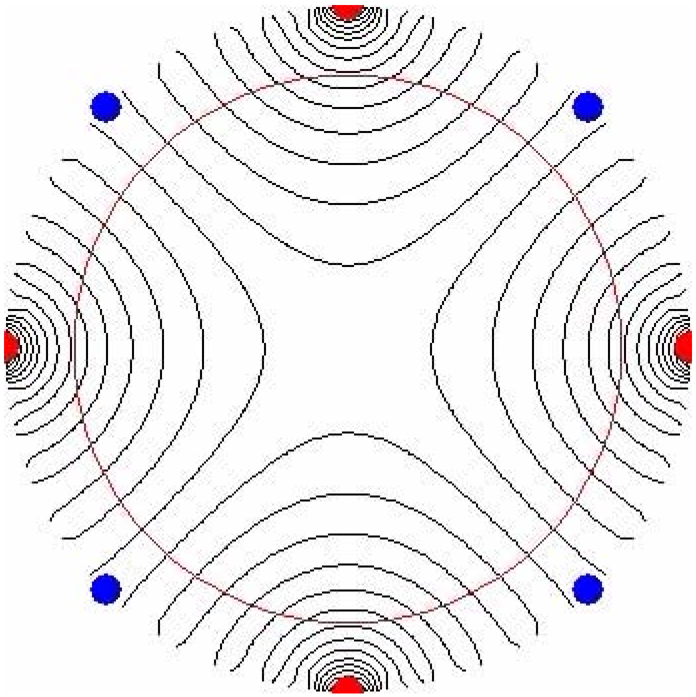


For a quadrupole: $$B_r = -\frac{4\mu_o I}{\pi} \sum_{n=2,6,10,...} \left\{ \frac{\cos(n\alpha)}{R_c} \left(\frac{r}{R_c} \right)^{n-1} \sin\left(n\theta + (-1)^{\frac{n+2}{4}} \omega t \right) \right\}$$

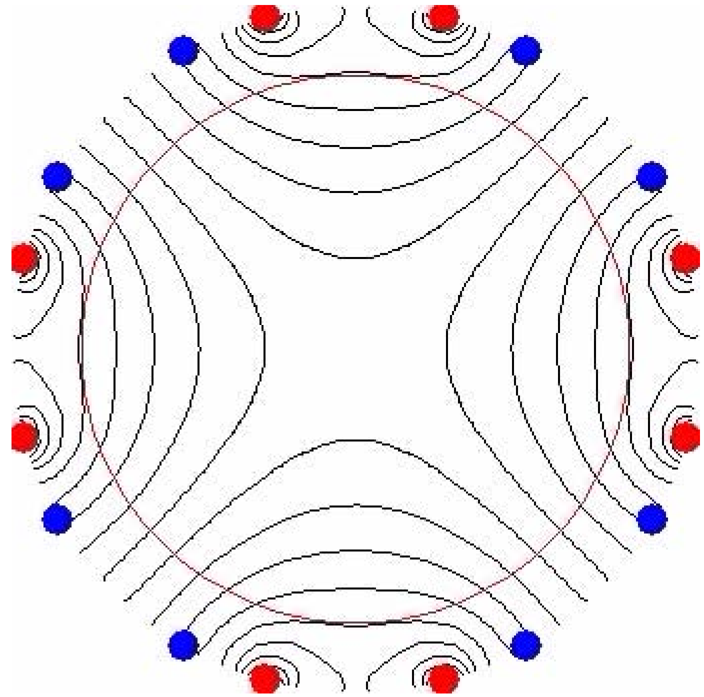
- Quadrupole field does not penetrate to $r = 0$ ($B_r \propto r$).
  - Not a problem since RMF is usually confined to the FRC edge.
- Coil separation of ½ angle α = π/12 → n=6 mode is zeroed (optimum angle)
- The rotation rate of the RMF field, $\omega_{rot} \propto ½\omega_{rmf}$

Vacuum Quadrupole Field

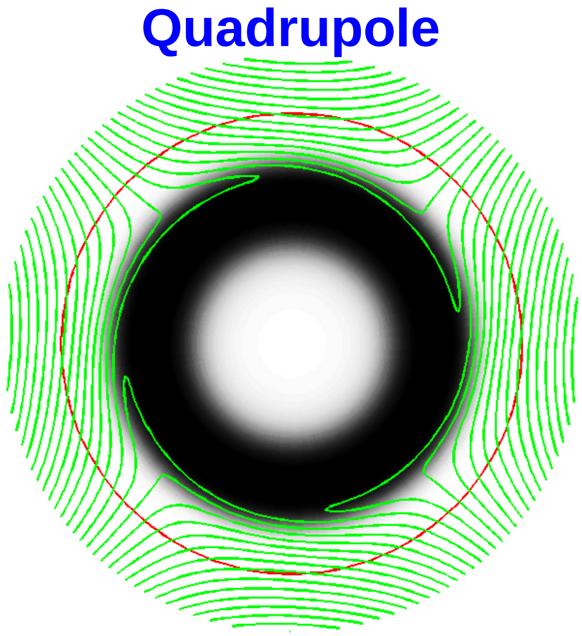
Simple quadruple coil set

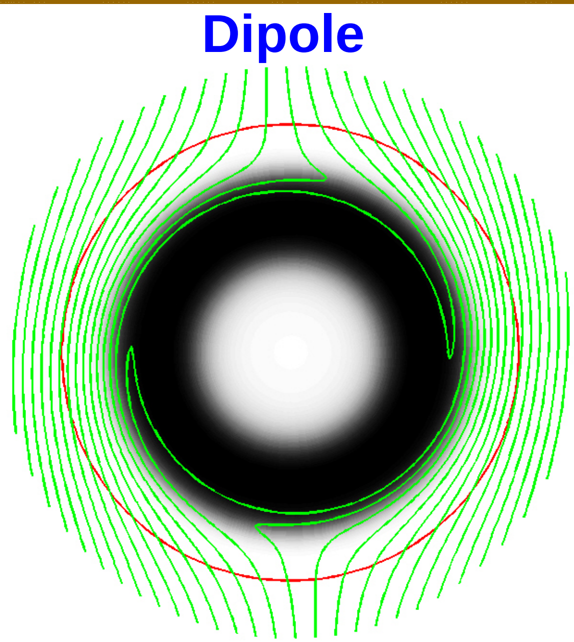


Quadrupole coil set: $\alpha = \pi/12$



Potential advantage to quadrupole





- Symmetric radial and azimuthal force on plasma
- Quadrupoles are known to stabilize n=2 rotational modes, and should be effective at centering the plasma
- For a constant uniform resistivity, numerical calculations predict slightly better current drive for quadrupoles.
- Reduce turbulence and lower resistivity?

MHD Model

$$\frac{\partial n}{\partial t} + \nabla \bullet n\mathbf{u} = 0$$

$$Mn\left[\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \bullet \nabla \mathbf{u}\right] = \frac{\mathbf{J} \times \mathbf{B}}{c} - \nabla P - \nabla \bullet \Pi$$

$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{u} \times \mathbf{B} - \eta c^2 \left(\frac{\mathbf{J}}{c}\right) - \frac{c}{en}\left[\left(\frac{\mathbf{J}}{c} \times \mathbf{B}\right) - \nabla P_e\right]$$

$$\frac{\partial S}{\partial t} + \nabla \bullet S\mathbf{u} = \frac{\gamma - 1}{n^{\gamma-1}}\left[\eta \mathbf{J}^2 + \nabla \cdot (k_\perp \nabla T) - \Pi : \nabla \mathbf{u} - R\right]$$

$$S = n^{2-\gamma} T$$

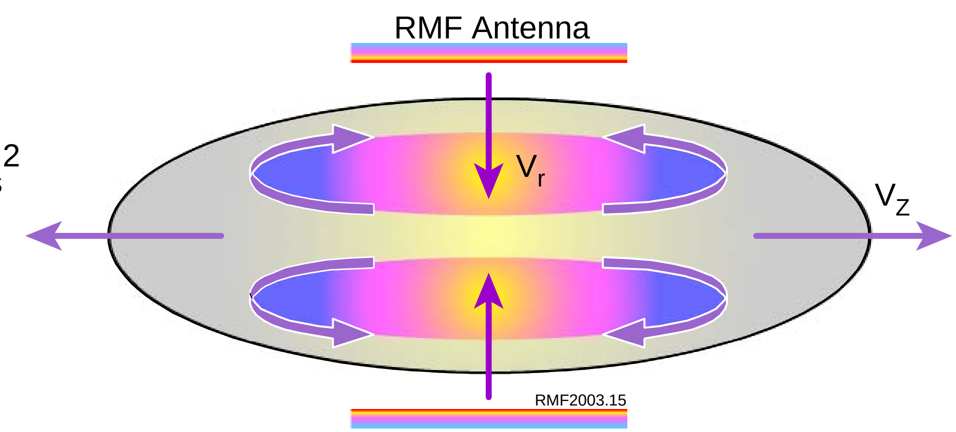
$$P = nk_B T$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$$

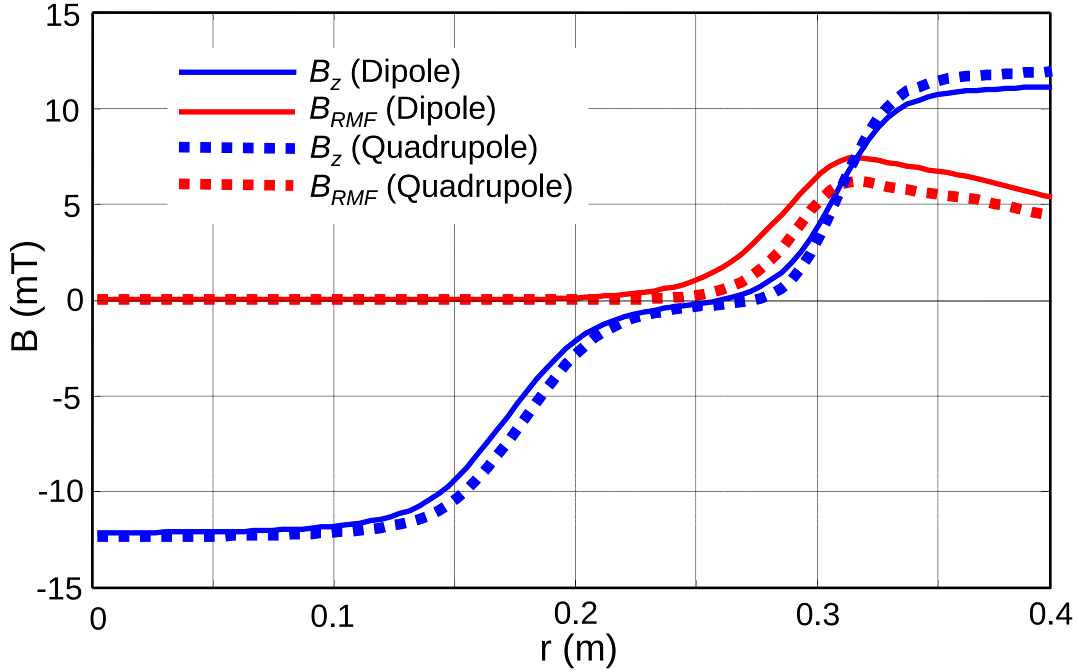
$$\Pi = -\frac{\mu}{Mn} \nabla \mathbf{u}$$

- Equations are solved numerically in the r-θ plane.
- To study FRC sustainment, two axial effects must be included:
  1. Average β condition: $<\beta> = 1 - \frac{1}{2} x_s^2$
  2. Equalization of temperature and density (pressure) between inner and outer field lines (including effects of rotation).

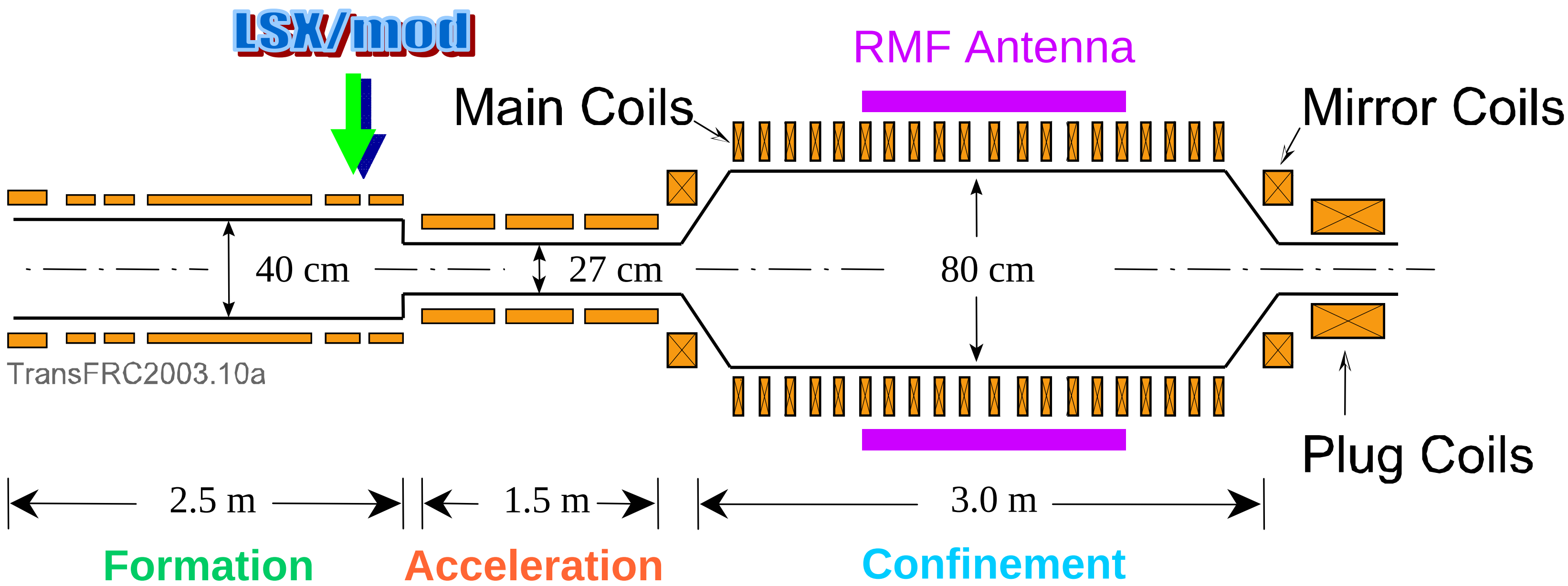


Numerical Predictions

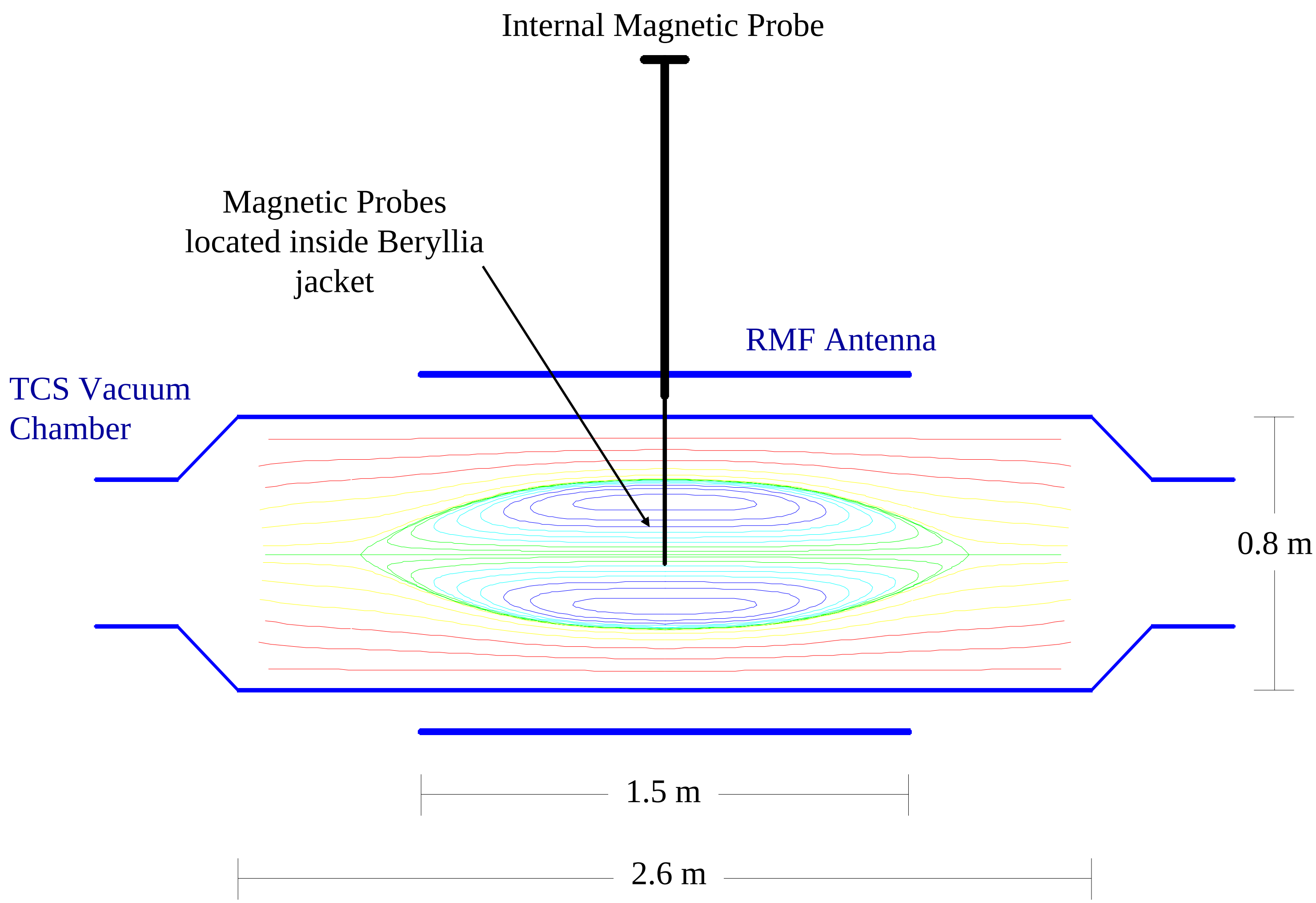
- Numerical simulations using RMF2 (a 2D (r-θ) Hall MHD code).
- Parameters similar to experimental parameters.
  - Uniform resistivity (η = 100 μΩ-m)
  - T_{total} = 30 eV, Vacuum $B_{RMF}(r = r_{wall})$ = 3.5 mT
  - f_{RMF} = 105 kHz (Dipole), 210 kHz (Quadrupole)



The TCS Facility



The Internal Magnetic Probe

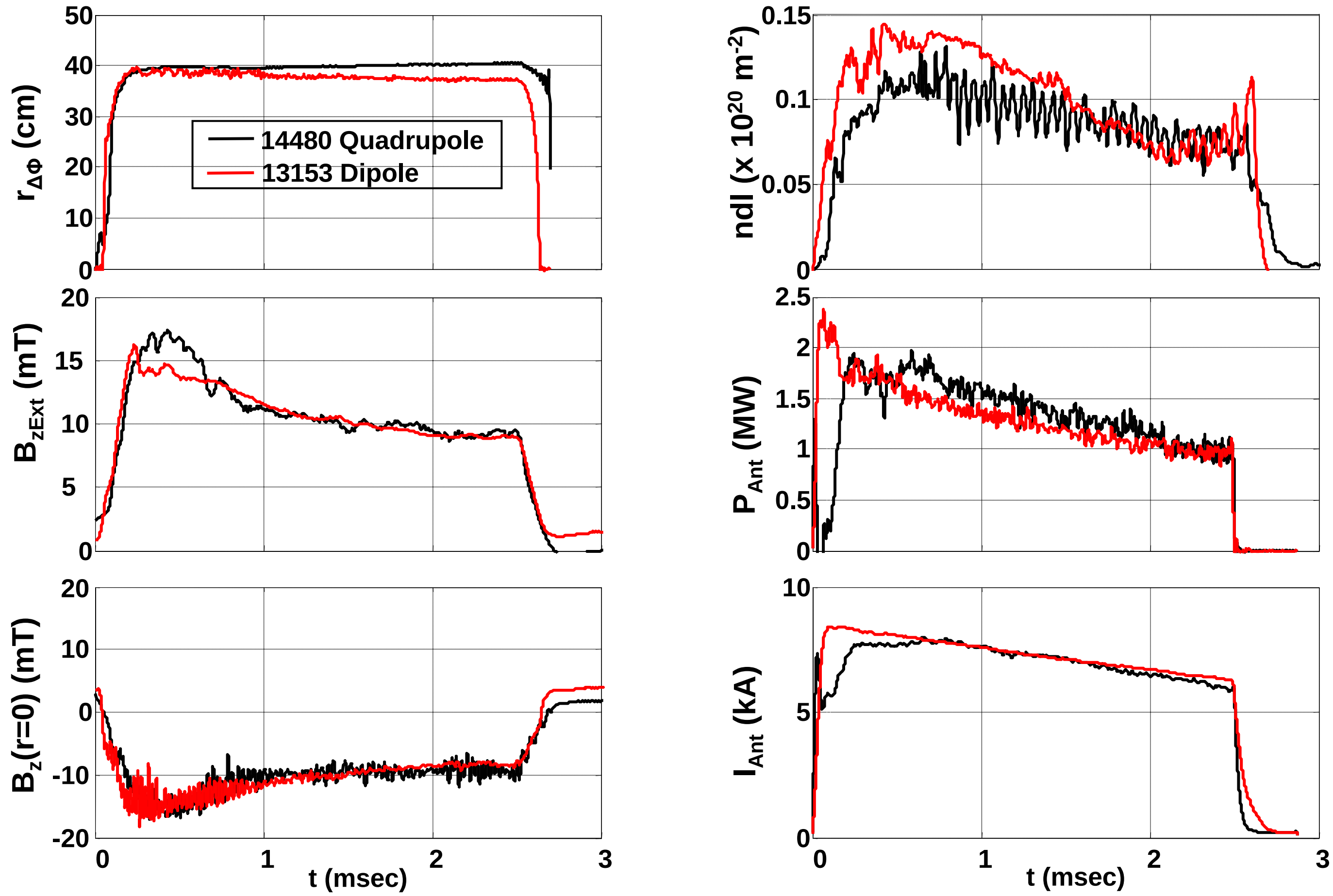


Signal Processing Internal Probe Data

- Probe can be aligned to measure B_x only, B_z only, or at 45º to measure both B_x and B_z.
- With the probe at 45º, so that both B_x and B_z are measured, it is assumed that:
  - The signal within ±10 kHz of f_{RMF} is RMF signal and is thus in the x-direction.
  - The rest is assumed to be in the z-direction.
  - This is not always a good assumption.

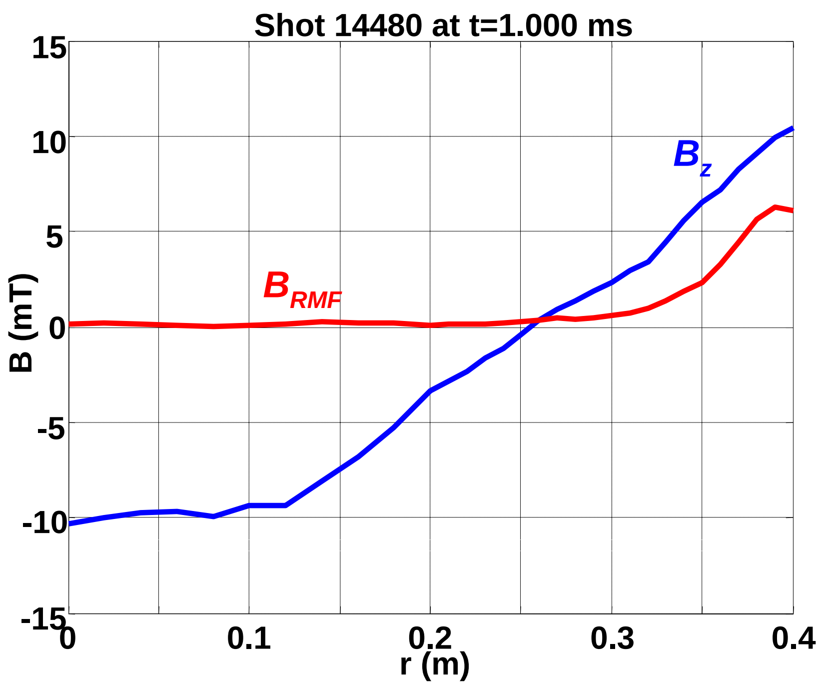
Experimental Results: Current Drive Efficiency

- Quadrupole RMF drives current as efficiently as Dipole RMF at given I_{Ant} and similar effective ω_{rmf}. (105 kHz vs. 260 kHz)

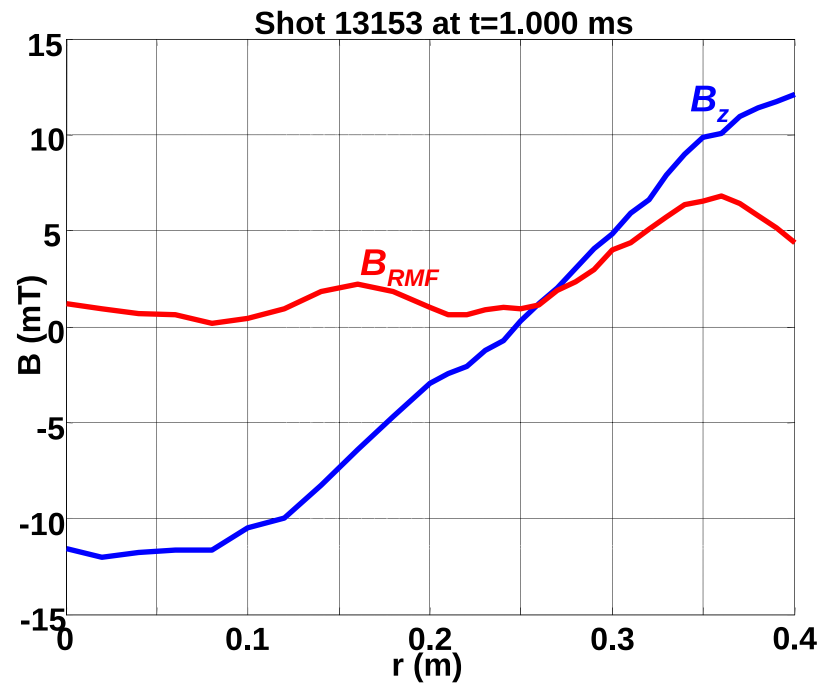


Internal Profiles

Quadrupole (ω=260 kHz)

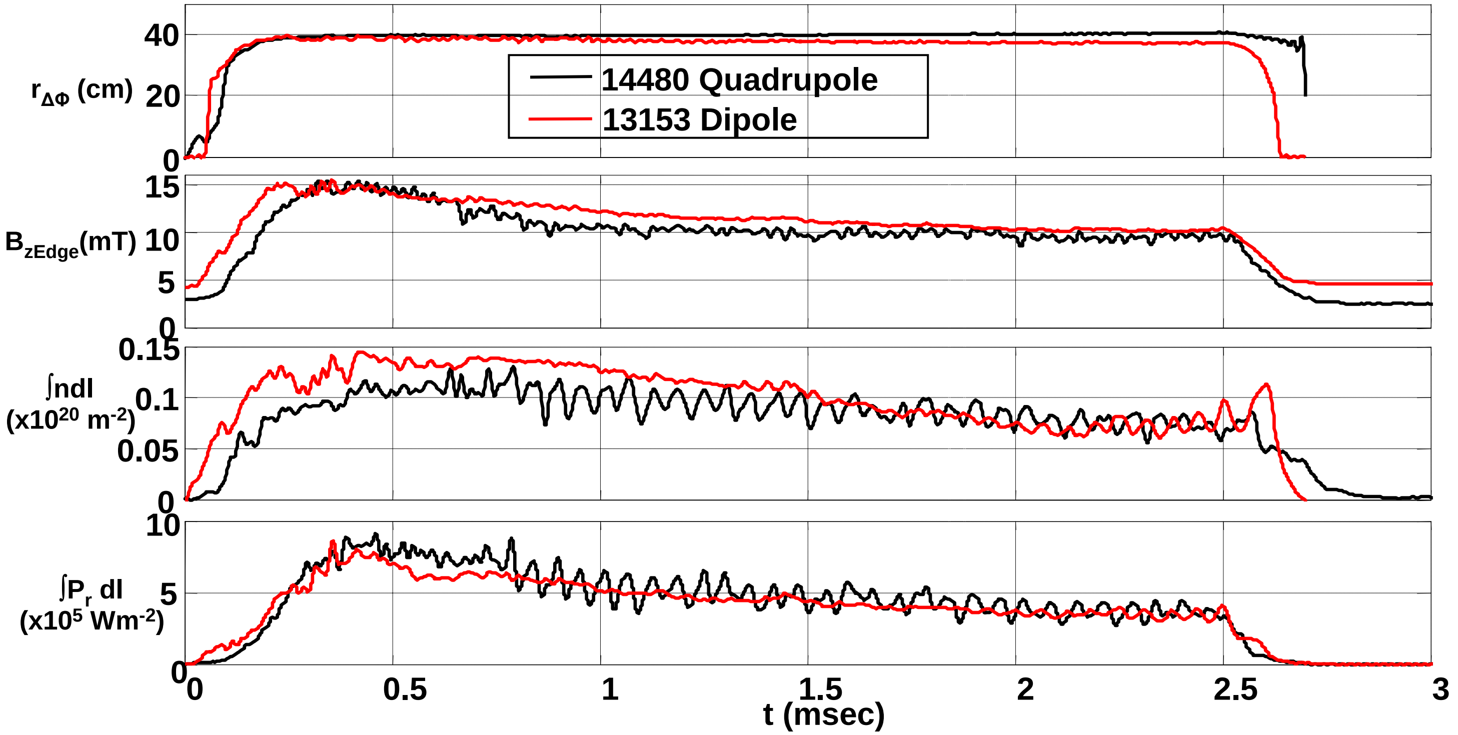


Dipole (ω=105 kHz)



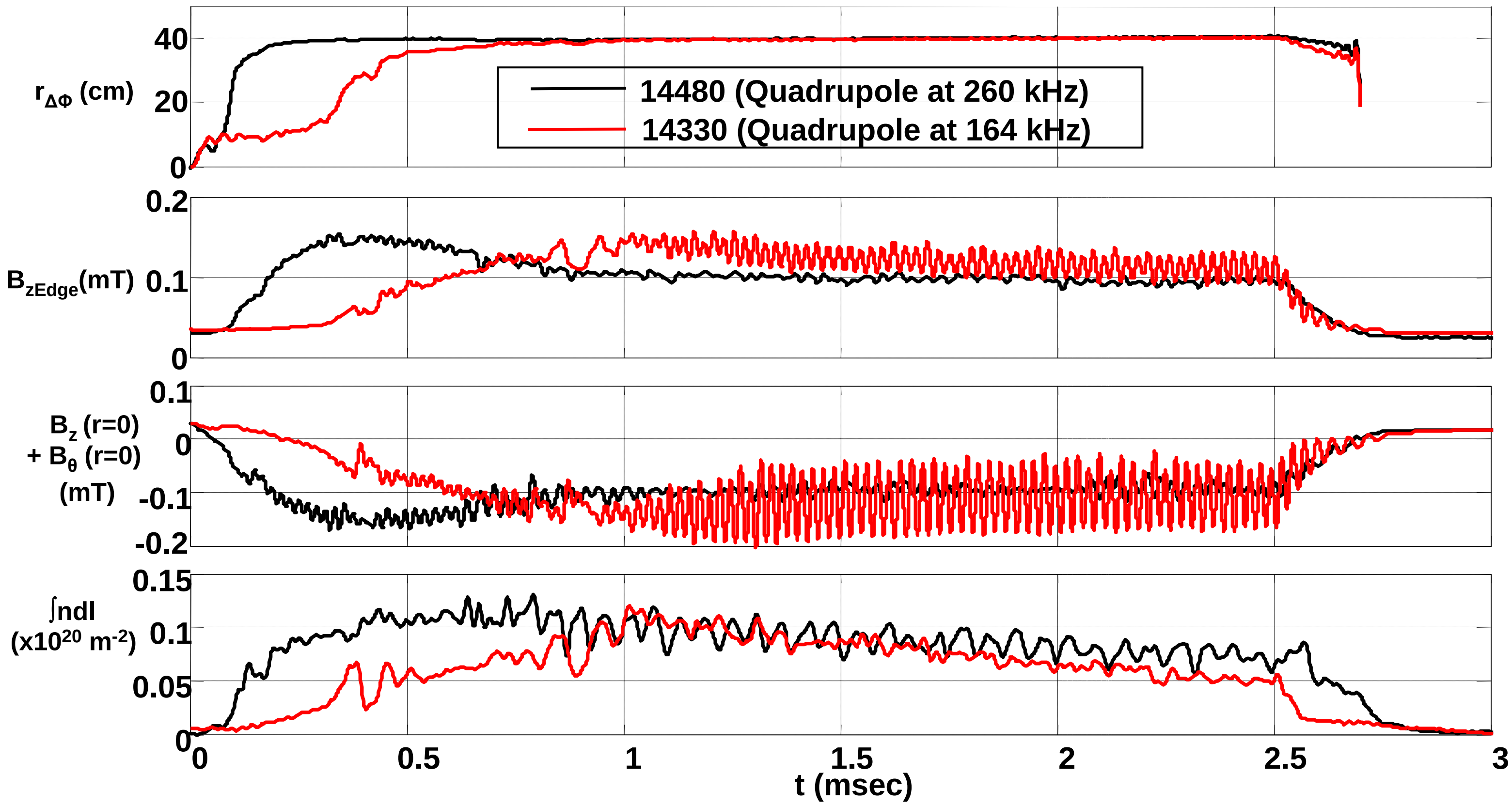
- **However, quadrupole RMF is more localized at the edge.**

More prone to n=2



- As a result, FRCs formed by quadrupole RMF is more prone to n=2, possibly due to insufficient RMF present near field null where centrifugal force is strong (*H.Y. Guo et al, this meeting*).
- f_{Rot} ~ 9 kHz, similar to the dipole case.
- As in the dipole case, reducing ω aggravates rotational instabilities.

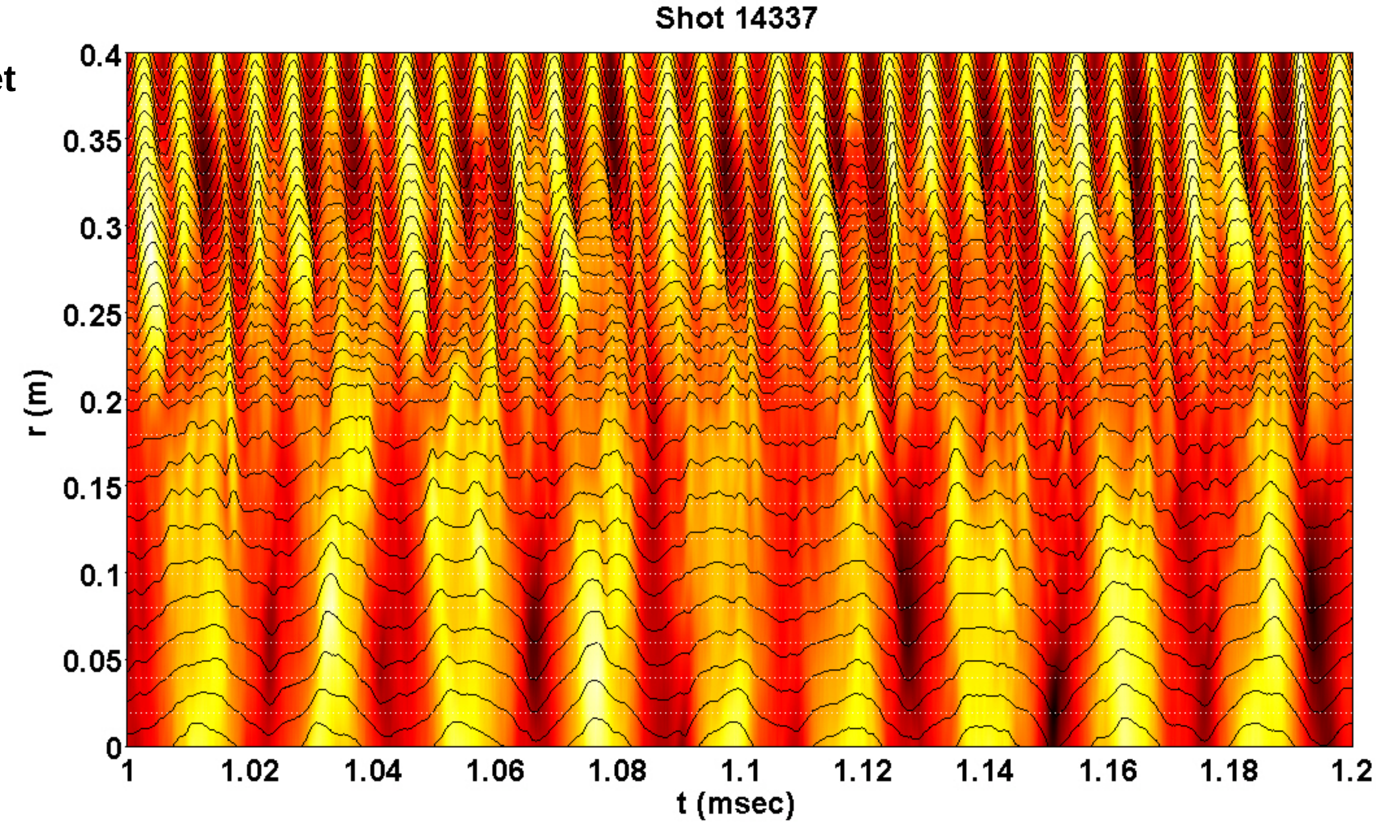
Stronger Internal Oscillations



- **Quadrupole RMF also leads to strong internal oscillations in B_θ, especially at lower ω, i.e., 164 kHz (#14330).**
- **Note that oscillations appear as r_s approaches the wall, and persist until the end of the pulse.**

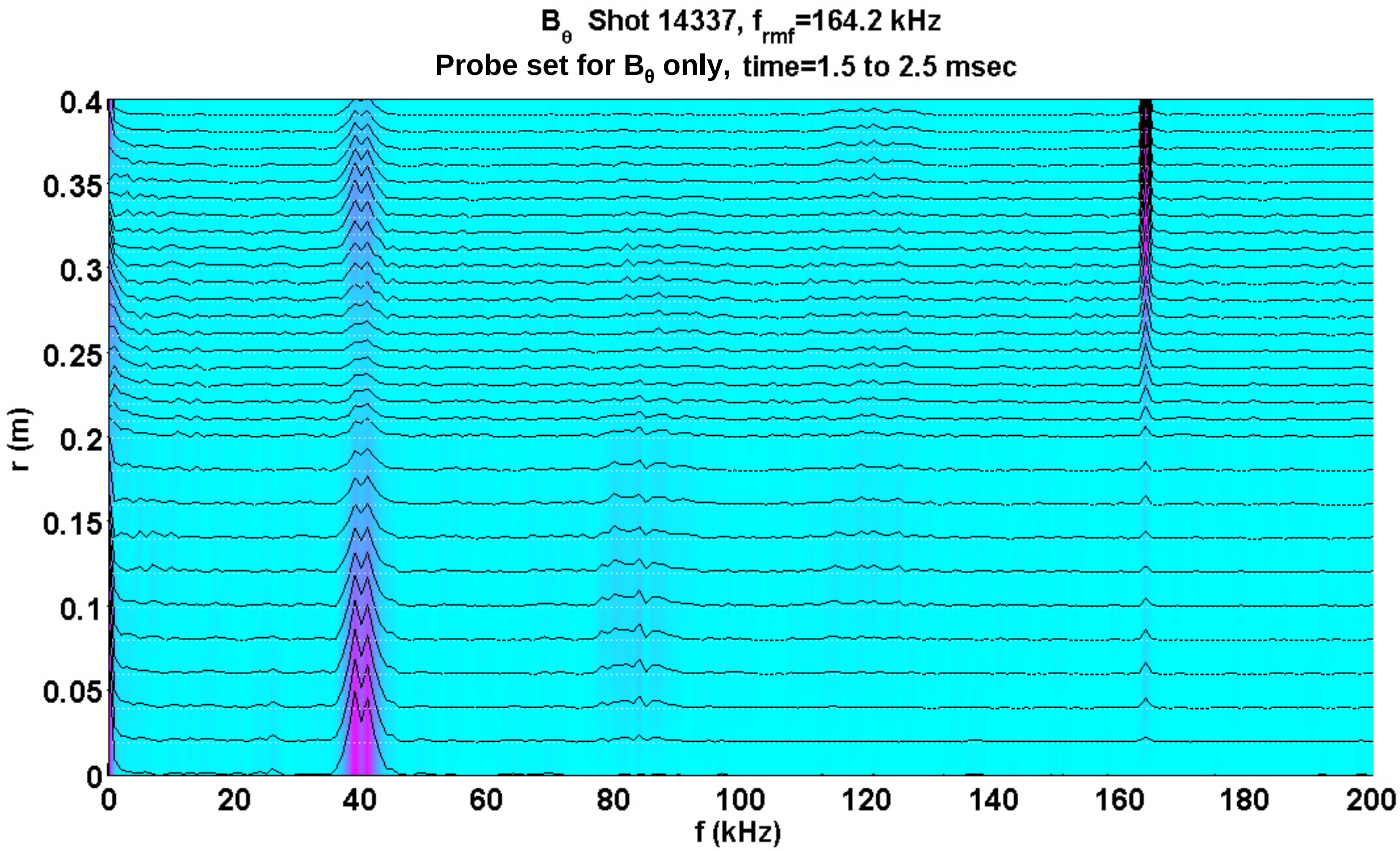
Internal oscillations in B_θ

Probe set for B_θ only



- Quadrupole RMF driven FRCs tend to develop low frequency internal oscillations in B_θ, especially at large x_s and low RMF frequency.
  - Large amplitude (comparable to RMF amplitude at $r = r_{wall}$.
  - Penetrate to $r = 0$.

Internal oscillation spectrum



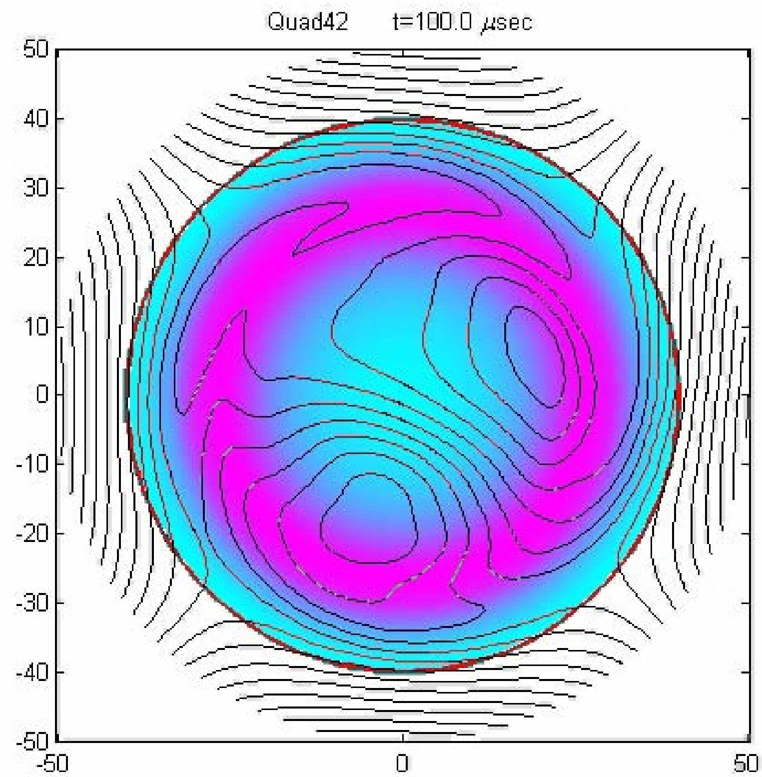
- The B_θ spectrum has a dominant low frequency spike.
  - Large amplitude at small and large radius.
  - ~180º phase shift between inner and outer regions

Inner mode structure

- Antennas produce a rotating n=2 field, which is confined to the outer region of the FRC.
- An internal n=1 field spontaneously develops, and fully penetrates the FRC (all the way to the null).
  - We believe that it is an n=1 field because:
    - It co-rotates with the electrons and produces a single cycle in the rotation time of the electron fluid. (The rotation frequency of the electron fluid can be calculated using the internal magnetic profile and the interferometer.)
    - It fully penetrates to r = 0 (higher order modes must vanish at the axis of symmetry)
- What is the source of the low frequency inner field?
  - Tilt ?

Numerical calculation with inner structure

- Numerical simulations using RMF2
  - a 2D (r-θ) Hall MHD code.
- Simulations do not spontaneously produce inner rotating structure.
- Simulations with an initial n=1 internal structure, and a resistivity profile that is sharply peaked near the edge yield signals similar to the experimental observations.
- Inner current is driven by the rotating internal structure.
- A torque is applied to the structure through the continuous tearing and reconnection of field lines (as in "*edge-driven mode*").



Summary

- Quadrupole RMF is as efficient as dipole RMF for a given antenna current,and similar effective ω_{RMF}. (Quadrupole antennas must be driven at double the frequency.)
- Quadrupole RMF is more localized to the edge.
- FRCs driven by quadrupole RMF are more prone to the n=2 instability.
- FRCs driven by quadrupole RMF are prone to large internal oscillations.
- The above observations → narrow operating range for quiescent, stable FRCs.